METHOD OF EVALUATING ABDOMINAL INJURY IN JAPAN'S CHILD-RESTRAINT-SYSTEM ASSESSMENT PROGRAM

Yuji Ono
National Agency for Automotive Safety & Victims' Aid
Yukikazu Komiyama
Ministry of Land, Infrastructure and Transport
Osamu Takatori
Japan Automobile Research Institute
Japan
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ABSTRACT

This paper describes the electric pressure sensor-based abdominal injury measuring method employed in the Japan's CRS assessment program.

The CRS assessment program was launched in 2001 in Japan[1] The objective of this program is to assess usability of CRSs for infants and toddlers and the systems' safety in frontal collision.

This assessment has started due to recent increase of casualties among minor passengers and to introduction of the mandatry use of CRSs for six-year-old or younger passengers.

The safety assessment test determines performance of CRSs by evaluating behavior of dummies and the target CRSs as well as damage caused by the CRS. It also investigates whether or not the CRS is constraining vulnerable parts of the child's body. In the initial plan, high-speed photography was to be used for determining the scale of the injury caused by restraining gear such as a harness on a child's body. It was found, however, that images from high-speed photography are not suited for determining degrees of compression on the abdomen, the most vulnerable part of the body. In order to solve this problem, we have started an investigation for an alternative method capable of quantitatively measuring abdominal compression.

Throughout the study, the electric pressure sensor-based method was employed for determining abdominal compression from the CRS assessment in 2003. This method allows for quantitatively observing the ever-changing pressure distribution on the abdomen. This approach first calculates abdominal loads from the pressure data collected from the area corresponding to the child's abdomen, and then selects the maximum load among them for use in the actual assessment. We have derived children's resistibility to abdominal load by scaling the relation between the waist belt and Abbreviated Injury Scale (AIS) among adults to the children's physique.

1. INTRODUCTION

In Japan, evaluation of usability of CRSs for infants and toddlers as well as safety of these systems in frontal collision has been conducted as part of the CRS assessment program since 2001.

In the frontal collision test, a cut body of Toyota's family wagon type Estima secured to the sled testing machine is caused to collide at a testing speed of 55km for an hour (see Figure 1). Safety of the CRS under test is evaluated based on behaviors of the dummies, degrees of damage on the dummies, scale of injury caused by the restraint and degrees of damage on the CRS body (see Tables 1, 2, 3 and 4)

In the usability evaluation test, five specialists is to assess ease of use of CRSs in the light of how they are protected from inappropriate usage. Usability of a system is rated for each of the evaluation items on a five-point scale from 1 to 5. Average of the scores on the five evaluation areas is then computed and published (see Table 5)
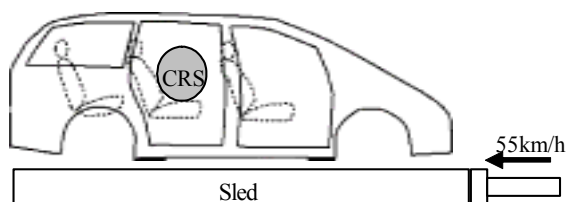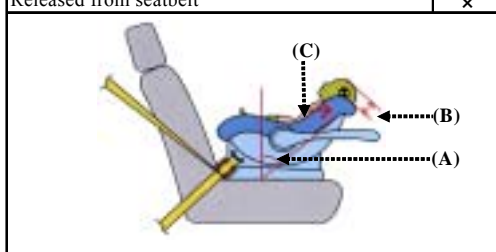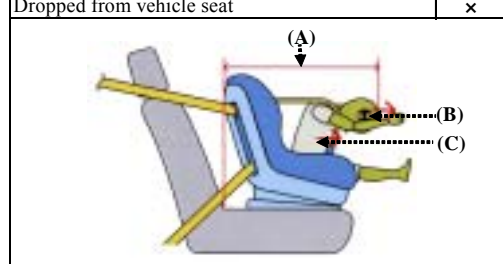

Figure 1 Test configuration

Table 1 Individual rating for rear-facing infant CRS

Rating items	Criteria	Rating
Damage of such as fixtures	No	
	Slight	
	Terrible	×
Inclination angle of seat back (A)	60deg. angle	
	60deg. angle 70deg.	
	70deg. angle	×
Projection of the head from CRS (B)	No projection	
	73mm projection	
	73mm projection	×
Chest resultant 3ms acceleration (C)	539m/s^2(55G) acc.	
	539m/s^2(55G) acc.	
Release of buckle		×
Released from seatbelt		×

Table 2 Individual rating for bed-type infant CRS

Rating items	Criteria	Rating
Damage of such as fixtures	No	
	Slight	
	Terrible	×
Restraining condition (Projection of the head from CRS, bottom angle of bed (A))	Rotating rearward (No projection of the head)	
	No rotation (No projection of the head)	
	Rotating forward or projection of the head	×
Head excursion in forward direction (B)	600mm excursion	
	600mm excursion 750mm	
	750mm excursion	×
Chest resultant 3ms acceleration (C)	539m/s^2(55G) acc.	
	539m/s^2(55G) acc.	
Release of buckle		×
Released from seatbelt		×

Table 3 Individual rating for forward-facing toddler CRS

Rating items	Criteria	Rating
Damages of such as fixtures	No	
	Slight	
	Terrible	×
Head excursion in forward direction (A)	550mm excursion	
	550mm excursion 700mm	
	700mm excursion	×
Head resultant 3ms acceleration (B)	785m/s^2(80G) acc.	
	785m/s^2(80G) acc.	
Chest resultant 3ms acceleration (C)	588m/s^2(60G) acc.	
	588m/s^2(60G) acc.	
Release of buckle		×
Released from seatbelt		×
Possibility of injury, such as that a harness press weak parts of the child's body (abdomen etc.).		×
Dropped from vehicle seat		×

Table 4 Overall evaluations for frontal collision test

Excellent	No "× " and the results of all 4 rating items are " ".
Good	No "× ", the results of any 3 rating items are " " and the result of the rest of rating item is " ".
Normal	No "× " and the number of " " is two or less.
Not recommended	If there is any "× " as the result of the test.

Table 5 Evaluation items used in usability test

Area	Target
Instruction manual, etc.	Instruction manual
	Package
Information on CRS	Information content
	Belt guide
Structural design	Movable structures (usability of reclining, rotation structures)
	Seat cover (ease of maintenance)
	Internal storage (for instruction manual, accessories)
Ease of installation (installation to vehicle seat)	Belt routing
	Installation
Ease of fitting	Harness
	Buckle
	Fitting

Each survey area is scored on a scale of 1 to 5, with a standard score of 3.

2. STUDY OF ABDOMINAL COMPRESSION EVALUATION METHODS

As to the vest-type CRSs, high-speed video was found to be incapable of determining the degree of abdominal compression caused by the worn harness because of complex behavior of the dummies during the test. We have therefore launched an investigation to find another abdominal compression measuring method and also to develop a well-defined evaluation method usable for this method.

2.1 Measuring Methods usable for Evaluating Abdominal Compression

Six measuring methods were examined for the above purpose, and usefulness of five of them has been verified in the tests similar to the frontal collision test used in the assessment program.

(1) High-speed photography

We have observed the state of the restraint applied to the dummies as well as their behavior using high-speed cameras. Two cameras were provided in the dynamic test; one was installed on the side position of the cut body to measure the amount of motion of the head and the other was placed on the front side of the cut body to observe the state of the restraint (see Figure 2) The front side camera was first set on the ground but then affixed to the cut body so that the relative distance between them will not be changed by movement of the cut body.
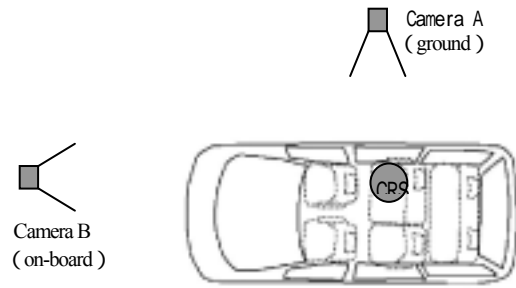
Figure 2 Layout of High-speed Camera
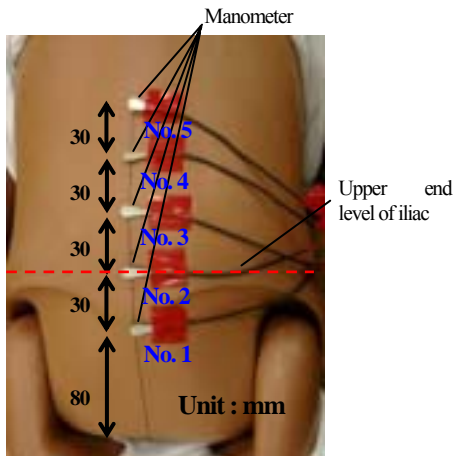
(2) Iliac bone load meter

We measured the load to the iliac bone after changing the original iliac bone of Hybrid III-3YO to Anterior Superior Iliac Spine (ASIS) load cell DENTON 3079. ASIS responses to the load in four separate areas of the right, left, top and bottom, allowing measurement for four channels of data for a single body of Hybrid III-3YO (see Figure 3)

(a) Human body   (b) Dummy
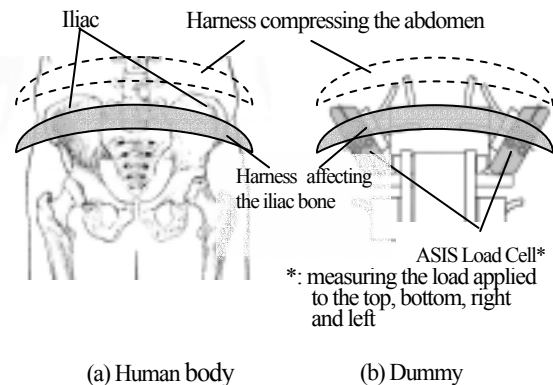
Figure 3 Image of ASIS Load Cell installed on Hybrid III-3YO

(3) Strain type manometer

Strain type manometers having a recipient pressure surface of 6 mm in diameter (KYOWA PS 1 MPa) were set at five positions along the centerline extending from the lumbar to the abdomen of the dummy (see Figure 4) With this arrangement, referencing outputs from the manometer allows us to observe where the harness is applied - lumbar or abdomen.

Figure 4 Strain Type Pressure Manometer installed on Hybrid III-3YO

(Figure labels: Manometer; No.5; No.4; No.3; No.2; No.1; Upper end level of iliac; 30; 30; 30; 30; 80; Unit : mm)

(4) Pressure-sensitive sheet

The dummy's torso was wrapped with FUJIFILM Prescale LW, the surface of which turns red depending on the magnitude of given pressure (see Figure 5) Measuring range of the pressure-sensitive sheet is from 2.5 to 10MPa. This was used to measure distribution of the stresses generated by the restraint on the dummy's torso.
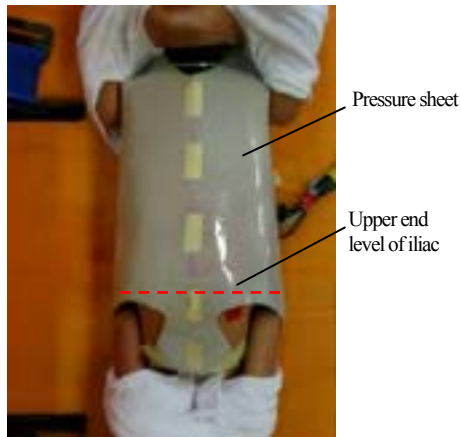
Figure 5 Pressure-sensitive Sheet installed on Hybrid III-3YO

(Figure labels: Pressure sheet; Upper end level of iliac)
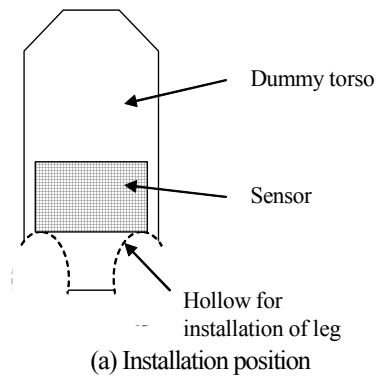
(5) Electric pressure sensor

A sheet-type, electric pressure sensor having approximately 0.1 mm in thickness, was installed on the dummy's abdomen to measure the applied pressure

there (see Figure 6)

The electric pressure sensor was placed so that the lower end of the sensor coincides with the upper end of the hollow for installation of the Hybrid III-3YO legs. The measurement area was set to cover the spaces beyond the abdomen (see Figure 7)
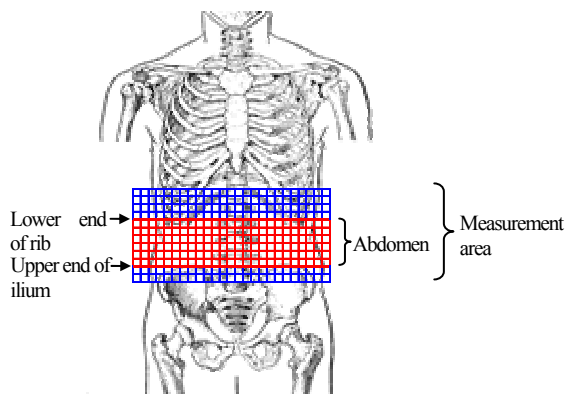
The TEKSCAN Tactile Sensor High Speed System complied with the following specifications was selected as the sensor. Major specifications are described as follows.

- Measuring range was from 0 to 1.96 MPa.
- Measuring area was 120 mm in the vertical direction and 250 mm in the horizontal direction.
- Measuring cells were arranged in 12 lines in the vertical direction and 25 columns in the horizontal direction, enabling measurement of the pressure in 300 divisions.
- Resolution of the analog-to-digital converter used was 8 bits or more.
- The sampling frequency was 500 Hz or more.

(Figure labels: Dummy torso; Sensor; Hollow for installation of leg)

(a) Installation position

(b) Actual situation

Figure 6 Electric Pressure Sensor installed on Hybrid III-3PO

Figure 7 Image of Electric Pressure Sensor's Measurement Areas

Lower end of rib →

Upper end of ilium →

}Abdomen }Measurement area

(6) Styrofoam

Inserting Styrofoam in the dummy's abdomen is used as a method of determining scale of injury caused to the abdomen by the submarine phenomenon (see Figure 8) This approach is intended to measure scale of abdominal injury by referencing the deformation caused on Styrofoam during the test. However, since this approach requires use of Styrofoam and retrofitting the dummy to accommodate Styrofoam, we gave up using it for the CRS assessment before conducting its the dynamic test.
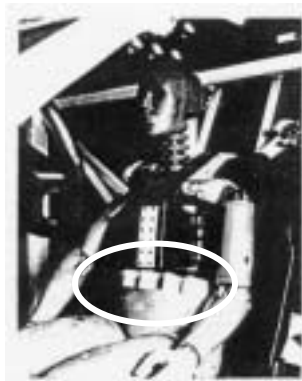
Figure 8 Styrofoam Installed in Hybrid III-3YO (Reference [2])

2.2 Study on Effectiveness in Frontal Collision Test

(1) High-speed photography

Figure 9 shows high-speed photos of the time when forward movement of the dummy's knees reached the maximum. We can recognize on the vest type test product that the waist harness that had originally been applied around the pelvis was pushed up due to the impact. It is, however, difficult to determine the degree of abdominal compression from the high-speed photos alone.

Sample A (vest type)

Sample B (vest type)

Sample C (shell + harness type)

Sample D (shell + harness + pad type)

Pad

**Figure 9 Check of Abdominal Compression by use of High-speed Photos**

(2) Iliac load meter

Figure 10 shows the time series data obtained from the iliac load meter. Loads to the right and left side are summed up as shown in the figure. The time when the combined load to the upper and lower part of the iliac becomes the maximum roughly coincides with the time when the forward movement of the dummy's knees reaches its maximum. The above finding indicates that the tensile force of the harness has a relationship with the load on the iliac.

With the vest type systems as well as the systems on which shell's shield is used for constraint, our measurement detected existence of the load in the pulling direction rather than the compressive load in the load applied to the upper part of the iliac. Such pulling load was essentially not observed on the harness type shell. It comes from the structural features of the iliac load meter - the meter measures pulling load in the upper iliac load as the dummy's abdomen is compressed.

The above findings seem to suggest that the upper and lower iliac loads increase even when the pelvis is securely constrained, and looser constraint generates a larger difference between them.
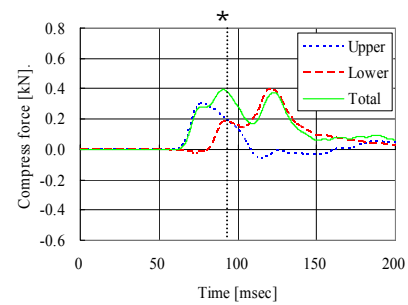
Since the iliac load meter reacts to external force not in the sensing direction, we must determine the meter's response patterns to various external forces before using it for the evaluation.
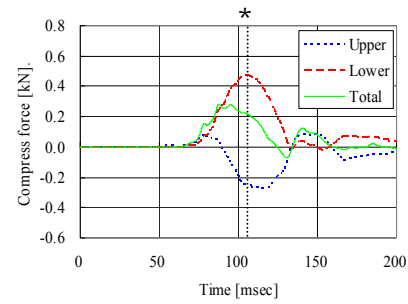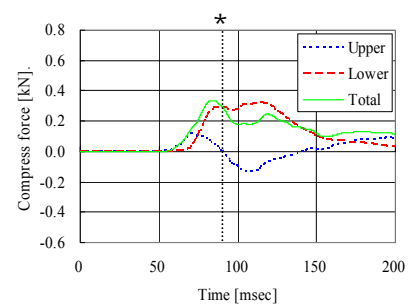
Sample A (vest type)
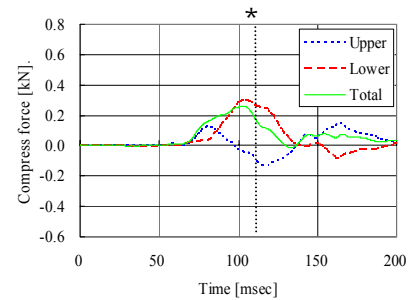
Sample B (vest type)

Sample C (shell +harness type)

Sample D (shell + harness + pad type)

Time when forward movement of the knees reaches the maximum.

Figure 10 Iliac Loads Measured by ASIS Load Cell

(3) Lumbar and abdominal manometer

Figure 11 shows the maximum pressure obtained from the measurements done at five points in the lumbar and abdomen. The sensor number is sequentially assigned in ascending order from the bottom. No. 2 sensor was placed at the boundary of the lumbar and abdomen.

On Sample C and Sample D of the shell type, pressure measured by No. 1 sensor was greater than that obtained from other measuring points possibly because of the compression applied to the manometer from the crotch harness routed right above No. 1 sensor.

On Sample C where the harness type shell was used, pressure measured by No. 4 and 5 sensors was greater than that obtained from other measuring points possibly because the buckle on the measuring point compressed the manometer.
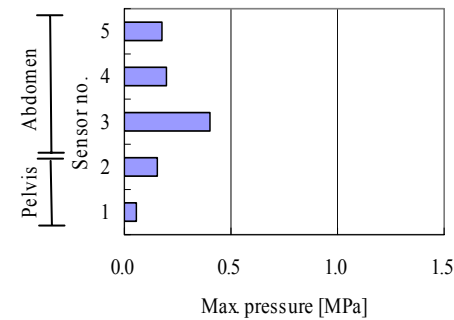
Measurement by use of the lumbar/abdominal manometer is available in limited areas only and pressure measurement beyond the measuring points is unavailable. The manometer protruding from the dummy's surface can interfere with the intended constraining behavior.
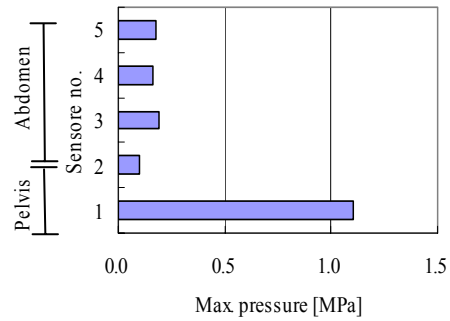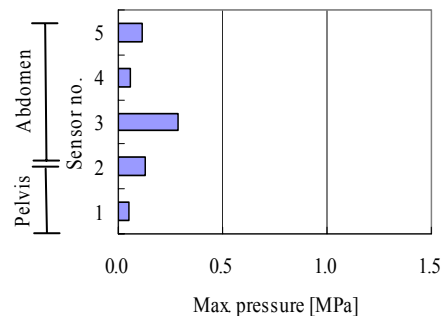
Sample D (shell + harness + pad type)
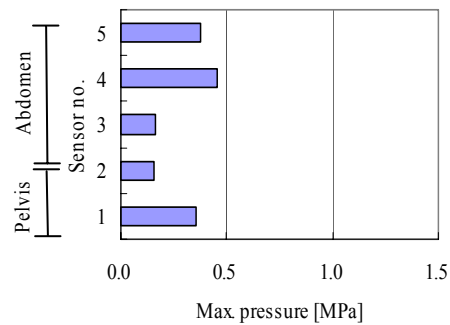
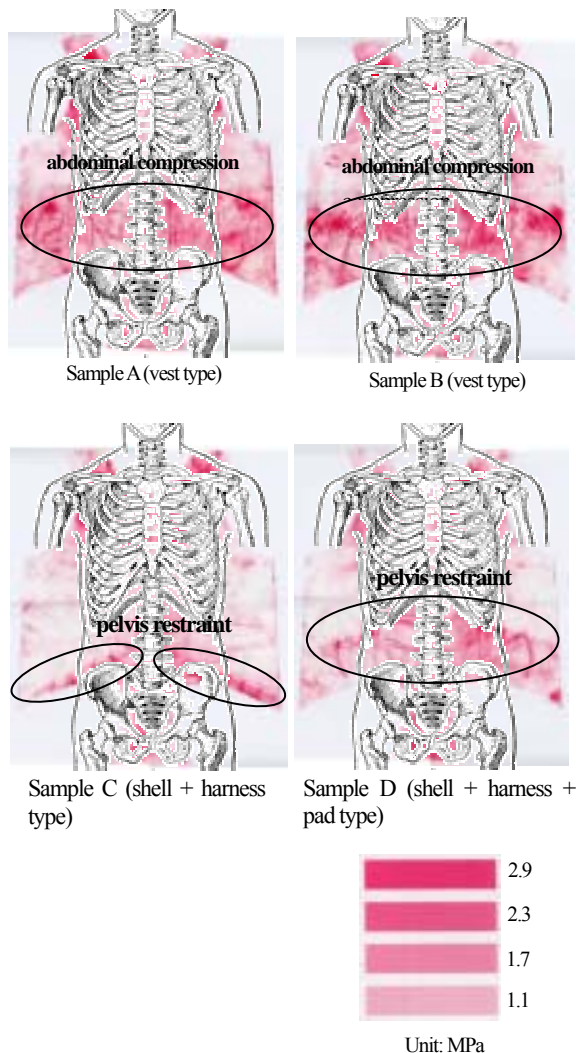Sample C (shell + harness type)

Sample B (vest type)

Sample A (vest type)

Figure 11 Pressures Measured by Lumbar/Abdominal Manometer

(4) Pressure-sensitive sheet

Figure 12 shows the pressure distribution obtained by use of the pressure-sensitive sheet. The color becomes darker as the pressure goes higher. With the vest type products tested, traces of relatively high pressure applied to the abdomen were noticed. While on Sample D where the shell type pad is used, relatively high pressure is generated in the abdomen by the pad as well as the lumbar harness situated at a higher position.

However, change in the color was also noticeable on the pressure-sensitive sheets that had been set in the areas completely free from constraint. In this case, change in the color must have resulted from friction on the sheet surface.

Sample A (vest type)

Sample B (vest type)

Sample C (shell + harness type)

Sample D (shell + harness + pad type)

	2.9
	2.3
	1.7
	1.1

Unit: MPa

Figure 12 Pressure Distribution measured by Pressure-sensitive Sheet

(5) Electric pressure sensor

In order to determine effectiveness of this sensor in measuring pressure to the abdomen (the most vulnerable part of the torso), measurements on abdominal pressure obtained from various systems were compared after removing pressure to the chest and lumbar. For the comparison, pressure to the abdomen was first converted to load on the measuring cell basis and the loads were added together. In the following, the added load is referred to as the abdominal load.
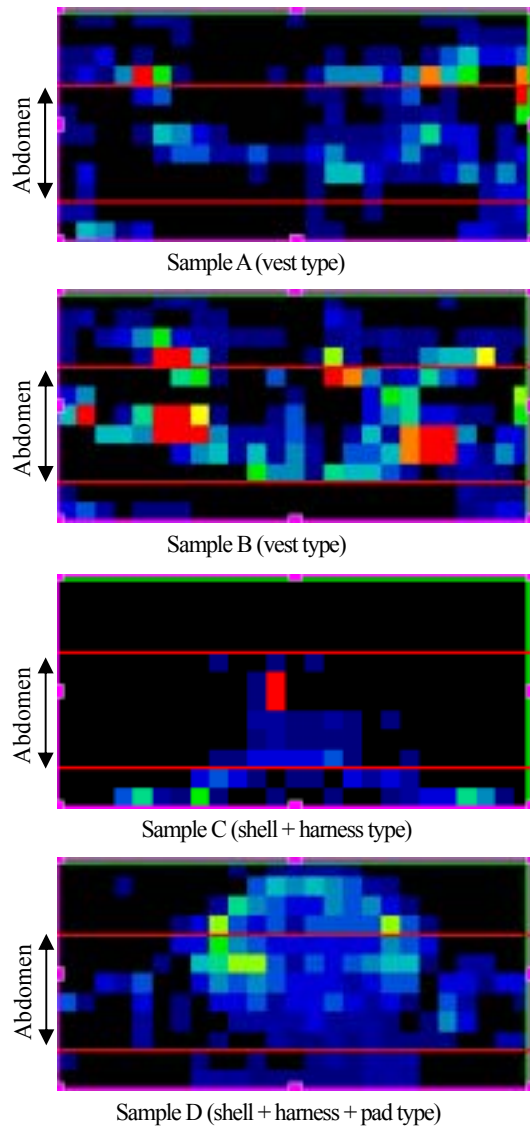
Figure 13 shows the pressure distribution at the time when the abdominal load grows to the maximum. With Sample A of the vest type, pressure is distributed over almost the entire abdomen. With Sample B also of the vest type, pressure distribution is noticeable in the center part of the abdomen where the lumbar harness is applied.

Figure 14 shows change in the abdominal load over time. The load data fairly coincides with the dummy's behavior.
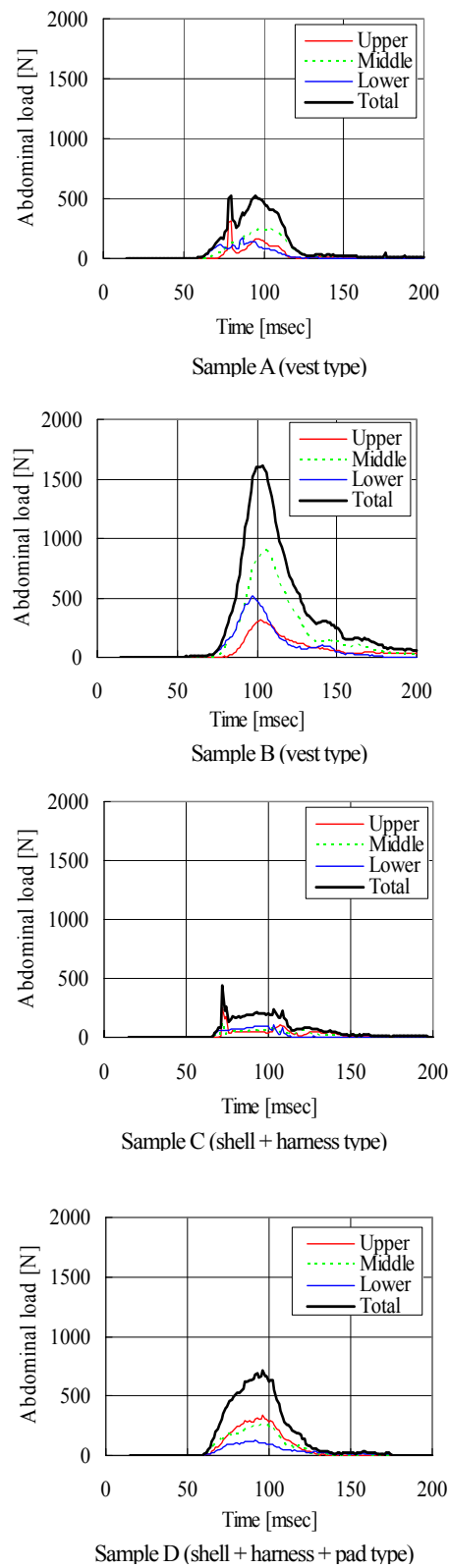
On various types of CRSs each using a different restraining method, we measured the pressure applied to the dummy's abdomen by use of the electric pressure sensor in the frontal collision test conducted under the same conditions as those used for the CRS assessment.

The sensor was capable of measuring the change in pressure distribution over time that is possibly caused by the harness and buckle of the respective CRSs. The above findings seem to well depict the features of the constraining method and behavior of respective CRSs.

These results prove that the electric pressure sensor is capable of measuring the pressure distribution overcoming the differences in the constraining methods or equipment shapes of the CRSs. This allows us to implement quantitative comparisons relating to the pressure applied to the abdomen. We have therefore decided to employ this approach for the evaluation of abdominal compression.

Sample A (vest type)

Sample B (vest type)

Sample C (shell + harness type)

Sample D (shell + harness + pad type)

Unit : kPa

Figure 13 Pressure Distribution as Abdominal Load reaches Maximum

Sample A (vest type)

Sample B (vest type)

Sample C (shell + harness type)

Sample D (shell + harness + pad type)

Figure 14 Changes in Abdominal Load over

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2.3 Abdominal Compression Evaluation Methods

Abdominal compression comprises two types of load - one is the load that is applied to broader areas in the abdomen and the other is the load that is applied locally by the harness or buckle. As to the local compression, there are no studies available today on characteristic response to or resistance of the human body to such loads. Therefore, this subject was removed from our current study.

As for the load applied to broader areas, there is a reference document describing the relation between the waist belt and Abbreviated Injury Scale (AIS) [3] among adult males We converted the adult males' resistance data to that of a 3-year-old child using scaling technique being employed by the Federal Motor Vehicle Safety Standards (FMVSS) [4, 5]

It is difficult in the frontal collision test to directly measure tensile force of the lumbar harness on a CRS.

Thus we measured the pressure on the abdomen instead of measuring tensile force of the lumbar harness on the above with pressure measurement in the abdomen. The abdominal load was used to relate the pressure data to the lumbar belt's tensile force. Our research results on the relation between the waist belt and abdominal load were used in the conversion of the waist belt tension to the abdominal load. Conversion of the pressure data to the abdominal load was done by first converting pressure at each cell to load and then summing up the respective loads in the abdominal part.

We gave up using the concept of impulse (the value derived by integrating load with time) as an index in evaluation of the abdominal load since its relation with injury currently remains uncertain.
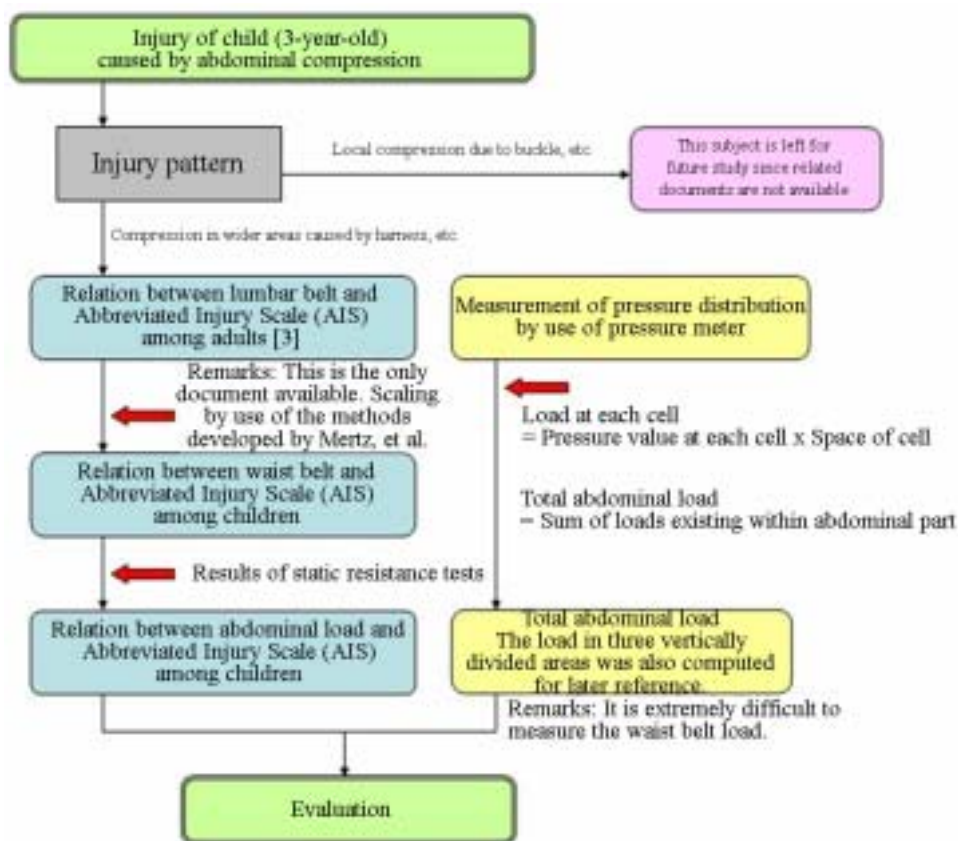

Figure 15 Concept of Abdominal Compression Evaluation Method

2.4 Resistance Value

(1) Resistance value of abdominal load in adult

Figure 16 shows the relation between the lumbar belt and abdominal injury among adult males. The findings were derived from the experiments conducted by using cadavers. If the waist belt's tensile force was used to represent the intersections of the approximate logarithmic curve and respective AIS level, AIS 0 (No injury) becomes 2.38 kN, and AIS 1　Minor　and AIS 2 (Moderate) become 3.20 kN and 4.31 kN, respectively. This is the only document that refers to the relation between the abdominal compression and injury scale.
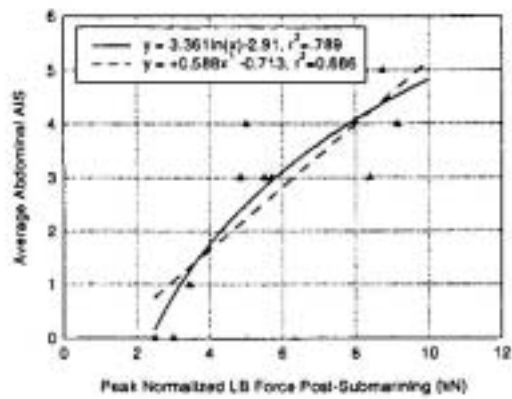

Figure 16 Relation between Waist Belt Tensile Force and AIS among Adult Males [3]

(2) Scaling of resistance values

We attempted to calculate the coefficient R_f that can be used in scaling the adult males' resistance value to that of three-year-old children. Since the coefficient for soft tissues such as the abdomen is not available, we employed the intensity coefficient of sinew λ_{of}.

Dimensional coefficient of the torso λ_Y and λ_Z were employed as the size-related coefficient [4, 5]

$$R_f = \lambda_{of}\,\lambda_Y\,\lambda_Z$$
$$= 1.0/1.18 * 0.556 * 0.602$$
$$= 0.284$$

As a result, AIS 0 became 0.68 kN　and AIS 1 and AIS 2 became 0.91 kN and 1.22 kN, respectively.

(3) Conversion from waist belt to abdominal load

A static test as shown in Figure 17 was conducted to determine the relation between the waist belt's tensile force and abdominal load measured by the pressure sensor. An electric pressure sensor was attached to the abdomen of Hybrid III-3YO with laid on a sturdy table with its face up. Then a weight was hung by use of webbing. With this arrangement, the relation between the weight and abdominal load measured by the electric pressure was investigated. Figure 18 shows the results.
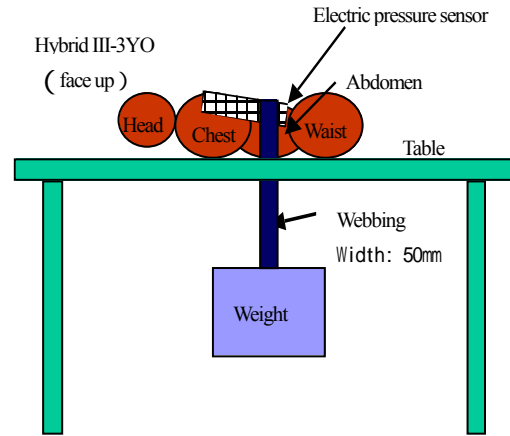

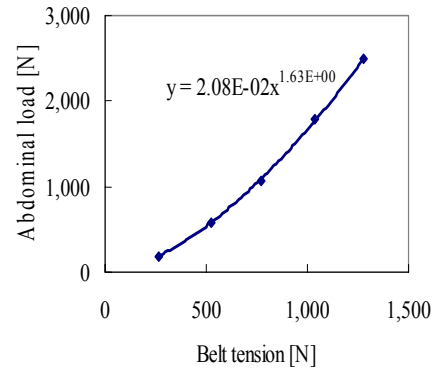**Figure 17 Electric Pressure Sensor used in Static Test**

Figure 18 Abdominal Loads measured by Electric Pressure Sensor in Static Test

From Figure 18, we can convert each AIS level to equivalent waist belt tension from the electric pressure sensor as follows - AIS 0 to 0.85kN, AIS 1 to 1.38kN and AIS 2 to 2.24kN.

(4) Study on resistance values

We can determine the relation between the degrees of injury and abdominal loads in children measured by the electric pressure sensor first by scaling the relation between the waist belt tension and injury among a body size of adult males and children, then by determining the relation between the waist belt tension and abdominal loads obtained from the electric pressure sensor. No injury results were found from the above study then the abdominal load measured by the electric pressure sensor was 0.85 kN or less. Injuries of AIS 1 level and AIS 2 level resulted from loads of 1.38 kN and 2.24 kN, respectively.

$$y = 2.062 \, \mathrm{Ln}(x) + 0.333$$
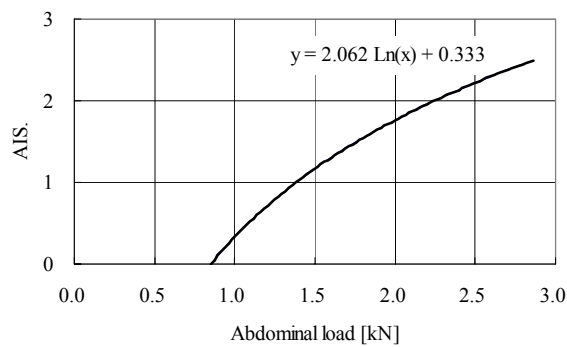
Figure 19 Relation between Abdominal Loads and AIS

2.5 Evaluation Method

Using the findings on abdominal loads corresponding to the injury level from AIS 0 to AIS 2, we have developed a tentative evaluation method. It is tentative because we could not find technical data or documents on characteristics of a baby's abdomen. In this approach, a four-level scale was set up for the evaluation as described below. Abdominal load equivalent to AIS 0 - "Abdominal compression is less likely", above AIS 0 up to AIS 1 - "Injury due to abdominal compression is likely", above AIS 1 up to AIS 2 - "Injury results from abdominal compression", and above AIS 2 - "Serious injury results from severe abdominal compression".

Table 6 Tentative evaluation criteria developed for this study

Abdominal load (AL)	Tentative evaluation criteria
AL ≤ 0.85 kN	Abdominal compression is less likely
0.85 kN < AL ≤ 1.38 kN	Injury due to abdominal compression is likely
1.38 kN < AL ≤ 2.24 kN	Injury results from abdominal compression
2.24 kN < AL	Serious injury results from severe abdominal compression

We attempted tentative evaluations using the above tentative evaluation criteria. We sorted the data by the pressure measurement data provided from CRS assessment 2002 (done by tentatively using the electric pressure sensor) and other research data by the constraint type (vest type, harness type, pad type and shield type). Load value of the harness type products is measured as "Abdominal compression is less likely" when constraint of pelvis is available in a static condition (see Table 7) Load value of one of the pad type as well as shield type products was rated as "Injury due to abdominal compression is likely".

There were substantial variations in the measured load values among the vest type products without the seat surface and backrest. The values ranged from "Abdominal compression is less likely" to "Injury due to abdominal compression is likely" and "Injury results from abdominal compression".

Table 7 Maximum abdominal loads measured

Main structure etc.	Abdominal load [N]
vest type A	529
	920
vest type B	1615
	1160
vest type C	647
	365
shell + harness type A	234
	153
shell + harness type B	155
shell + harness type C	134
shell + harness type D	110
shell + harness type E	469
shell + harness type F	693
shell + harness + pad type A	716
	748
shell + harness + pad type B	568
	564
shell + harness + pad type C	890
shell + harness + pad type D	694
shell + shield type A	829
	860
shell + shield type B	395
shell + shield type C	724

The threshold 0.85 kN between "Abdominal compression is less likely" and "Injury due to abdominal compression is likely" may appear to be a large load, but this load is the maximum value of the dynamically applied loads and not a constantly applied static load. If you drop a basketball from 5.9 m, resulting impact load on the floor surface is 1.02 kN, namely greater than the threshold (see Figure 20) Unlike the results in the frontal collision test, load values of every product of the traditional harness, and almost all pad type and shield products were the threshold.

These CRSs are used over a long time and there is no report that claims of abdominal injury are remarkable among the children using these products. It seems therefore reasonable to set the pass or fail threshold at 0.85 kN. We are considering employing this evaluation of abdominal compression as one of the items in the frontal collision test for children, "Possibility of injury, such as from a harness pressing weak parts of the child's body."
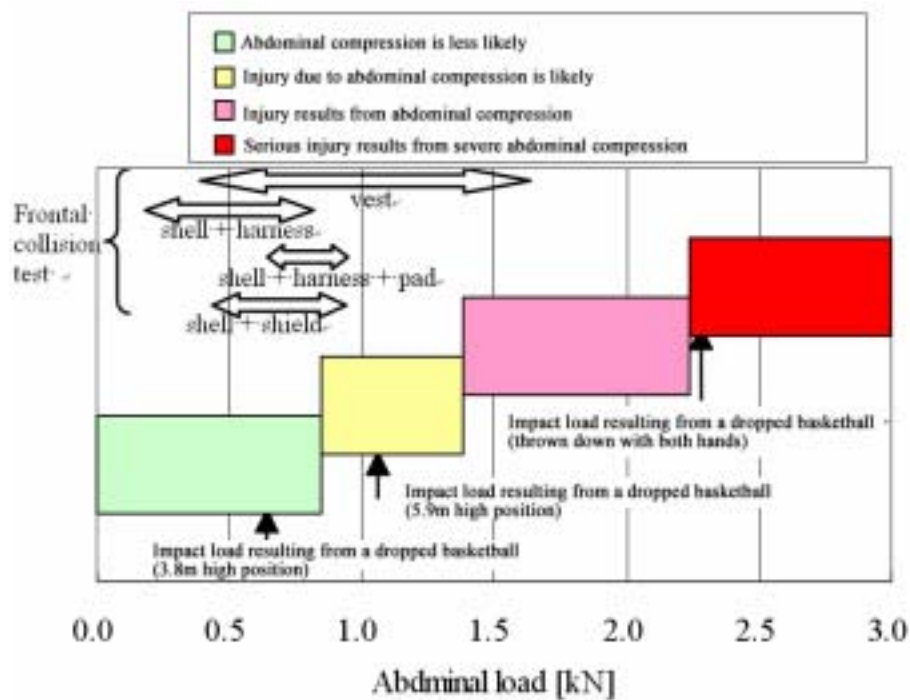

Figure 20 Impact Loads resulting from various Tests

3. SUMMARY

The above findings suggest that measurement of abdominal compression by a pressure sensor is effective and the measurement-based evaluation method is useful in comparing the degree of compression to abdomen. This approach therefore has been employed as a means for evaluation in the assessment program.

It would be effective in preventing injury due to the so-called bite from the harness to compare abdominal loads in the three vertically divided areas in the abdomen by use of the pressure sensor. If significant differences were detected among them, it would be useful to warn the users of the potential danger of bite from the harness.

It is difficult to quantitatively evaluate the influences of abdominal compression being locally applied by the harness or buckle since there is no available report on their resistance values or characteristics. Thus, evaluation of injury due to local compression is left as a subject for future study.

4. RESULTS OF EVALUATION OF ABDOMINAL COMPRESSION IN CRS ASSESSMENT 2003

Evaluation of abdominal compression by use of the electric pressure sensor was officially started from the 2003 CRS assessment. In the CRS assessment of 2003, seven products were selected as the target of evaluation [6]. Among them, abdominal compression was tested on six products - three seats for toddlers and three other seats for both infants and toddlers. One of the toddler's seats was a vest type CRS.

Figure 21 shows results of the test. Abdominal loads beyond the threshold 1.38kN were measured on the vest type product alone. However, we could not install the waist belt of this product in a position to sufficiently cover the pelvis despite the instructions provided in the manual. Thus only the result of each category is given here instead of providing a holistic evaluation of the product.

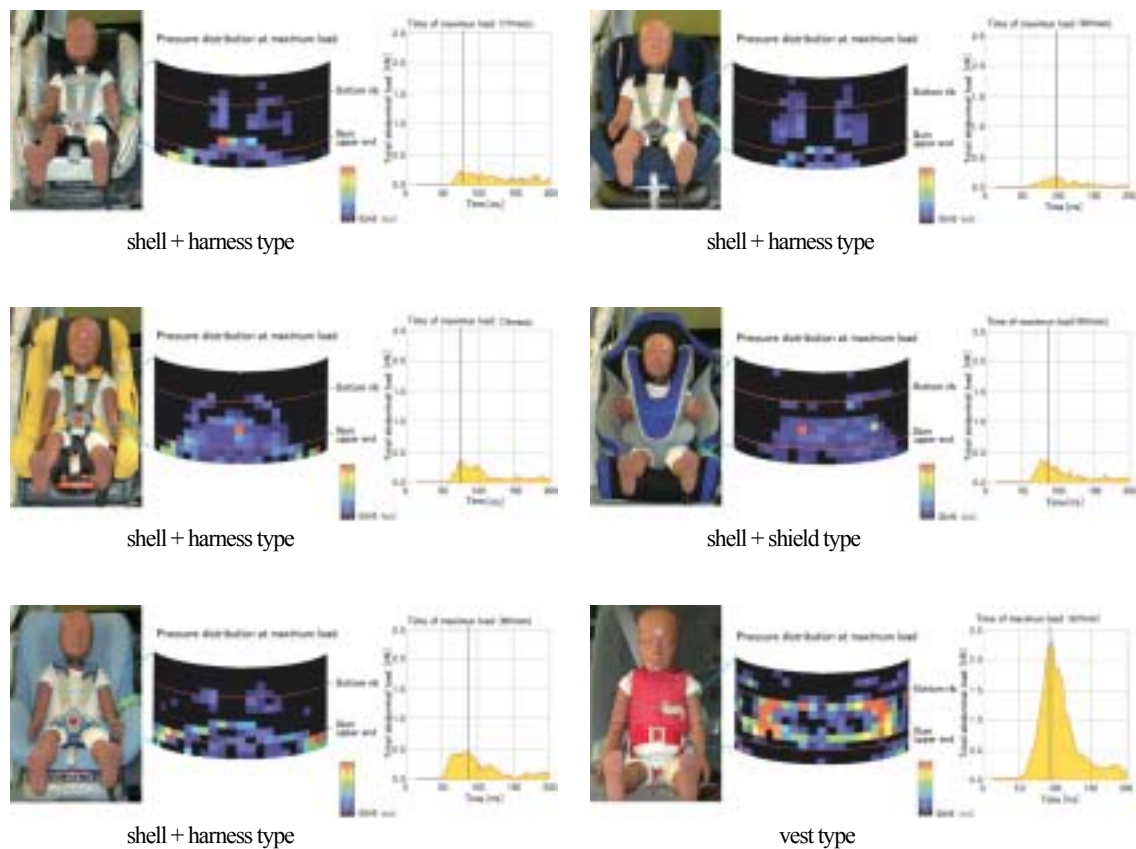No other products produced abdominal loads beyond the threshold.

shell + harness type

shell + harness type

shell + harness type

shell + shield type

shell + harness type

vest type

Figure 21 Results of Evaluation of Abdominal Compression in CRS Assessment 2003

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